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AUTOMATION OF PIPE WELDING USING MACHINE VISION AND ADAPTIVE CONTROL

François Nadeau*, Jacques Blain* and Marc Dufour**

ABSTRACT

A method to measure and control in real time the penetration of the root pass in butt joints has been found at the Industrial Materials Research Institute. The technology was applied to the development of a fully automated pipe-on-positioner welding system that performs both root and filler passes for joining ordinary carbon steel pipes and fittings. Using the GMAW process, the whole operation on a 6" pipe takes less than 5 minutes compared to more than half an hour for manual SMAW. The machine uses artificial vision and adaptive feedback to actually control the penetration during the root pass ensuring a defect free weld.

INTRODUCTION

If we think of the construction of an oil refinery, a chemical processing plant, a thermal power plant or even of a nuclear reactor, it is easy to see that pipe fitting is one of the most common operations in arc welding. In Canada alone, more than 50,000 tons of piping is assembled each year. Close to 70% of the joints are welded in pipe prefabrication shops with the assembly rotating on a positionner (1G position). Astonishingly, although this very repetitive process seems an ideal candidate for automation, most of it is still done manually using SMAW.

This is in sharp contrast with the general field of welded fabrication, usually very permeable to automation technologies. The prolific development of resistance welding and arc welding robots, and their generalized use in the automotive industry are striking examples. Why has the pipe welding industry not followed this trend? Because pipe fitting, however common, is still one of the most difficult operations in arc welding. The consequences of in-service failure in high pressure piping can be catastrophic and therefore quality requirements are amongst the highest. For the welder, it is quite a challenge to meet those requirements. The core of the problem is performing that ever so critical full penetration root pass which must join the inner edges of the open butt joint (fig. 1), the typical preparation for industrial pipe fitting.

* TECNAR AUTOMATION LTD
** INDUSTRIAL MATERIALS RESEARCH INSTITUTE (NRCC)

This operation requires extreme dexterity from the welder who must dynamically control the shape and motion of a pool of liquid metal suspended between the edges of the joint to ensure full penetration of the root. It is not surprising that, even done manually, most defects still occur in the root pass.

Whenever possible, industry works around this problem by developing procedures that do not require a full penetration open root. Some well known examples are: double sided preparations (pressure vessels, ship building), where the internally welded root pass is subsequently removed by back-gauging or grinding; also GTAW welding of closed butt joints with machined and bored preparation that eliminate misfit and other geometrical variations (boiler tubes). However, for industrial pipe fitting, small pressure vessel manufacturing and even small diameter pipeline construction, there is no alternative to the full penetration open root. Therefore, the development of a machine able to perform that operation opens up to automation technology an extremely vast and untapped market.

Automation of the full penetration open root pass

Performing a "full penetration" root pass requires the complete fusion of the joint's inner edges. In an open, V groove butt joint, as depicted in figure 1, the weldpool hangs from the joint preparation on either side and from the solidified weld metal in the back. Nothing supports it from beneath nor in front. Surface tension and viscosity compensate the pull of gravity

and maintain equilibrium. It is the interaction of these mechanical forces that determines the shape of the weldpool and the level to which it sinks between the edges of the joint, i.e. the penetration. These forces, in turn, are a function of the temperature distribution in and around the weldpool, the weight or volume of the weldpool and finally the geometry of the joint preparation right in front of it (gap, land, misalignment).

Ideally, if all these factors could be kept constant, a single set of adequate welding parameters could be experimentally determined and automation of the operation would be easy. In reality, this is all but impossible. For example, the cost of machining out the ovality and thickness variations of pipes would be prohibitive. The geometry of the joint is therefore never the same, as gap, land and alignment vary within certain tolerances (some of these even change during welding due to weld induced deformation). The temperature of the workpiece also varies as it heats up during welding. The welding process therefore has to be constantly adapted to those variations along the joint. This implies, of course, a capacity to monitor in real time the effect of these changes on the welding process.

How can a welder perform, joint after joint, a defect free full penetration root pass? The answer is simple: he is looking at what he is doing and reacting to what he sees according to his experience. Aside from an extremely steady hand, a good pipewelder has two key abilities: One is the capacity to diagnose in real time the state of the process (lack or excess of penetration, torch centering, etc...) by direct observation of the weldpool.

The other is the knowledge of how to adjust the welding parameters to maintain good weldpool conditions. An experienced welder will describe the shape, motion and even color of a weldpool with impressive detail. He, in fact, measures penetration as it occurs and "plays" with certain parameters on which he has immediate control (welding speed, torch angle, oscillation, etc...) to insure a defect-free root weld. At any given moment, he cannot tell the exact value of these parameters, but he knows they are right. In other words, because he is operating in direct "feed back", he does not require a quantitative model of the process. All he needs is a "control strategy", which he develops from experience.

This is exactly the approach that was taken at IMRI to automate this process. The use of indirect measurements, such as laser vision (1) and thermography (2), would have required the development of a model to relate the data to penetration depth because these sensors measure conditions around the weldpool. Instead, our efforts were focused on weldpool image analysis as seen through an ordinary video camera. We developed an algorithm that performs, on the image, diagnosis very similar to what the welder does and then adaptively changes welding parameters through a control strategy. The strategy is derived from an experimental data base. This is the basis of our method (3) to automate full penetration open root welding.

Similar to a welder's eyes and hand, the system digitizes 15 times per second the full image of the weldpool, analyses its shape and reacts on process parameters, constantly adapting to varying conditions such as changes

in gap, alignment, root face or even temperature. Fast reaction times allows it to work at high deposition rates and travel speeds where weldpool conditions are much too critical to be sustained by hand.

Description of the system

In order to test the method on a large sample of welds and in a shop environment, an "industrial" prototype was developed. The system automatically performs entire 1 G girth welds (root, fill and cap) on standard wall (sch. 40) or extra heavy (sch. 80), 4", 6" and 8" diameter carbon steel pipes and fittings. The drawing in Figure 2 illustrates the welding arm of the system performing a root pass on a 6" pipe. Two GMAW torches and a camera are mounted on the arm which pivots away when the weld is completed to clear the workpiece for unloading. A lateral slide allows oscillation of the torches and also seam-tracking. The straight torch is the one which operates in conjunction with the vision system and executes the root pass. The transfer mode is short-arc. The shielding gas is 75% Ar, 25% CO_2. The wire is .035" E70S-7. When the root pass is finished, the second torch is automatically activated and the weld is completed with one or more spray transfer passes. An Ar-2% O_2 shielding gas is then used. For these fill and cap passes, there is no adaptive control and a set of fixed parameters (a different set for each pass) is preprogrammed in the machine.

The video camera is of the industrial, solid state type. It is aimed directly at the weldpool and is equipped with optical elements that enhance

the contrast between the weldpool and its surroundings. The video signal is fed to a frame grabber that digitizes one out of every two video frames (15 frames per second). Figure 3 presents a typical image of the weldpool as seen by the computer. The colors represent various intensity levels which are used to detect the position of certain objects in the image, such as the arc, the wire tip, the joint's sidewalls and the weldpool bottom. Each frame is analyzed by the computer, an IBM PC AT which eventually extracts from these dimensional measurements, two numbers: the weld penetration error and the seam tracking error. This last information is used to center the torch in the joint. The weld penetration error is then fed to the algorithm controlling the various welding parameters, which are: travel speed, wire feed rate, arc voltage and oscillation width. The control strategy determines the relation between these parameters, whereas the sign and amplitude of the corrections applied to these parameters depends on the filtered value of the penetration error. All this is illustrated in the schematic diagram of Figure 4.

The picture in Figure 5 shows the entire prototype. Its main components are the welding head, comprizing the arm and the support rolls, the positionner, which can move on rails to accommodate spools of various lengths, the welding power source with the two wire feeders, gas bottles and water cooling unit, and finally the controller which includes the IBM PC and the interfacing electronics.

Test results

More than a thousand welds were performed while developing and fine-tuning the system. From the early results of more than 50% rejects, the process has been refined to produce high quality welds advantageously comparable to those of a good pipe welder. The productivity, however, is incomparably higher: the machine is at least four times as fast as manual SMAW.

This was confirmed on the last "production run" of about a hundred and fifty welds on coupons of 4", 6" and 8" diameter A-105 carbon steel pipe, both standard wall (SCH40) and extra heavy (SCH80). The welds were radiographed and mechanical tests were performed on about one out of three. Thirty coupons were cut up for root and face bends, 10 others were used for charpy V-notch impact testing and 8 for tensile tests. The results indicate that the system consistently produces code acceptable welds (ASME section IV) with a repair ratio of less than 5%. Radiographic defects were mostly porosity with the occasional lack of penetration. The bends were consistently good although hairline openings were observed in some root bends, mostly at tie-ins with tacks. Impacts in the weld metal (at -9°F) varied from 90 ft/lb. for $\frac{1}{2}$" thick, 8" schedule 80 coupons to 20 ft/lb for $\frac{1}{4}$" thick, 4" schedule 40 coupons. As expected, metallographic examination showed that the last "capping" pass has a less resilient unrefined microstructure and that, obviously, it occupies a greater proportion of the total weld section for thinner pipes. Impacts in the heat affected zone were clustered around 50 ft/lb (standard deviations of 15 ft/lb). Tensiles, performed at room tempera-

ture, yielded typical numbers for this material: yield strength between 40,000 and 50,000 lb/in^2, tensile strength from 53,000 to 72,000 lb/in^2 and elongation of 15% to 25%. To achieve these results, three major problems had to be solved. They are - 1) lack of penetration defects in the roots, 2) inclusions and lack of fusion in the fills and 3) impact resistance of the welds.

Lack of penetration defects will occur if the preparation of the joint is not within machine tolerances. The grinding of tacks is of particular importance. If they are not properly feathered, the extremities of a tack may not fuse properly into the weld and can create a defect. There are also some restrictions on the land thickness, gap width and misalignment of the joint. The graph of Figure 6 gives the "safe" operating range for land and gap. We see that these two parameters are not independant, i.e. the system can tolerate thinner lands if the gap is narrow. In addition, misalignment cannot be greater than plus or minus half the gap. Except for misalignment, if joint geometry exceeds the machine capabilities, the system will "saturate" at either end of its operating range, indicating an increased defect probability. This behaviour can be observed when running over tacks. Sensing that it cannot fully penetrate the weld, the system saturates at the high end of the range to get maximum penetration. On a tack, this does not cause a defect if the tack itself is well penetrated. Upon leaving the tack, these parameters produce an excessive penetration. This is immediately sensed by the system which will rapidly slow down to more adequate values. This is illustrated in the graph of Figure 7, where travel speed is plotted as a func-

tion of time for a typical root pass on a 6" diameter pipe.

For fill and cap passes, weldpool conditions are very reproducible and therefore, once a valid set of parameters has been found, it can be used over and over without any adaptive feedback. Obviously, that approach could not be applied to very thick sections where the laying of a large number of passes requires a substantial amount of decision making from an experienced operator. Automation of multipass welding is still an unsolved problem. However, in the range of thicknesses for which the system was developed (up to 1/2" on an 8" schedule 80 pipe), it was found more than adequate.

To program the machine, one has to define the total number of passes desired for each of the six pipe types. Then, for every pass, welding parameters (travel speed, wire feed rate, arc voltage, oscillation width) are optimized. The fill torch operates in a slightly downhand position. In this position, the weldpool's own weight lightly pulls it forward which helps eliminate undercut. Travel speed is then particularly critical. Welding too fast causes silica inclusions since there is no interpass grinding. Welding too slow lets the weldpool ahead of the arc causing lack of fusion defects. The prototype did not allow variation of the torch position and angle. This would have greatly reduced the criticality of the welding speed. Arc voltage is adjusted in conjunction with wire feed rate to stabilize the arc. Oscillation is used to optimize the bead profile and prevent side wall lack of fusion.

There is always a natural tendency to develop parameter sets with high wire feed rates as this results in smoother spray transfer and faster weld times. The limiting factor, of course, is heat input which decreases the impact resistance of the welds. It is well known that better impacts are generally obtained using a larger number of smaller passes because grain refinement occurs over a greater proportion of the weld area, provided that the interpass temperature is not too high. On larger diameter pipe (8"), the thicker wall already means more passes and further increases can be achieved without lengthening total welding time simply by raising travel speed. If the diameter is large enough, the delay between passes is sufficient to allow the heat to flow out of the weld and keep interpass temperatures at reasonable levels.

As the diameter goes down, everything becomes more critical. To get good impacts on the 4" schedule, 40 coupons for example, wire feed rate had to be reduced from 350 to 225 I.P.M., in order to squeeze in a third pass in the welding procedure and keep interpass temperatures at acceptable levels. Alternate solutions were considered, such as the use of micro-alloyed wires that limit grain growth in the weldments. However, it was found that the hotter two-pass procedure also tended to lower impacts in the heat affected zone. Thus, for small diameter pipe, the process has to be tuned down to slower, cooler parameters. On the 4" schedule 40, this means three minutes of welding time per joint instead of two. It is still much faster than manual SMAW, which takes approximately 15 minutes for the same weld.

CONCLUSION

Over all, these tests show the tremendous potential of this technology for increasing productivity in pipe fitting shops. It is a well known fact that converting from SMAW to GMAW yields very significant productivity increases on most welding applications. However, manual GMAW, particularly at high deposition rates, is a much greater challenge for the welder who must keep up with the process and maintain weldpool control while sustaining the heat from the high power arc. It is therefore not surprising that, after a brush with semi-automatic welding, many companies proceed to completely automate a particular welding operation in order to implement high deposition rate processes. But for applications, such as industrial pipe prefabrication, where a full penetration open root pass is required, preprogrammed, nonadaptive automation does not work. IMRI's penetration control technology provides, for that whole sector of the welding industry, the means to fully implement automated GMAW. This may be an important factor to capital investments in the energy sector, where labour, especially for welding, is a major part of the total cost.

References

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Figure Captions

Figure 1: Typical preparation (top) and completed weld (bottom) used in industrial pipe prefabrication.

Figure 2: Welding arm performing a root pass on a 6" sch 40 pipe.

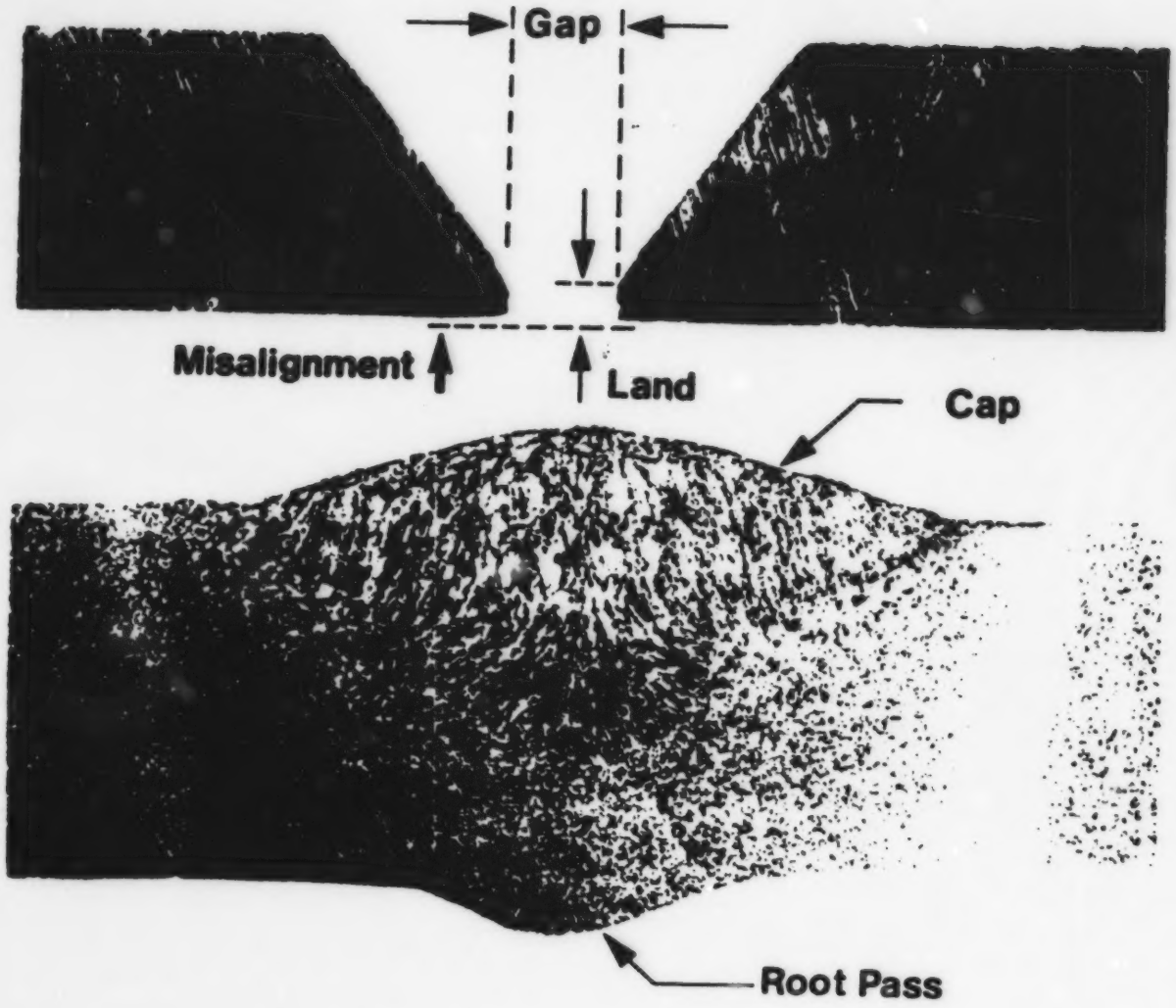
Figure 3: Image of the weldpool, as seen through the computer's eye.

Figure 4: Functional diagram of the penetration control system.

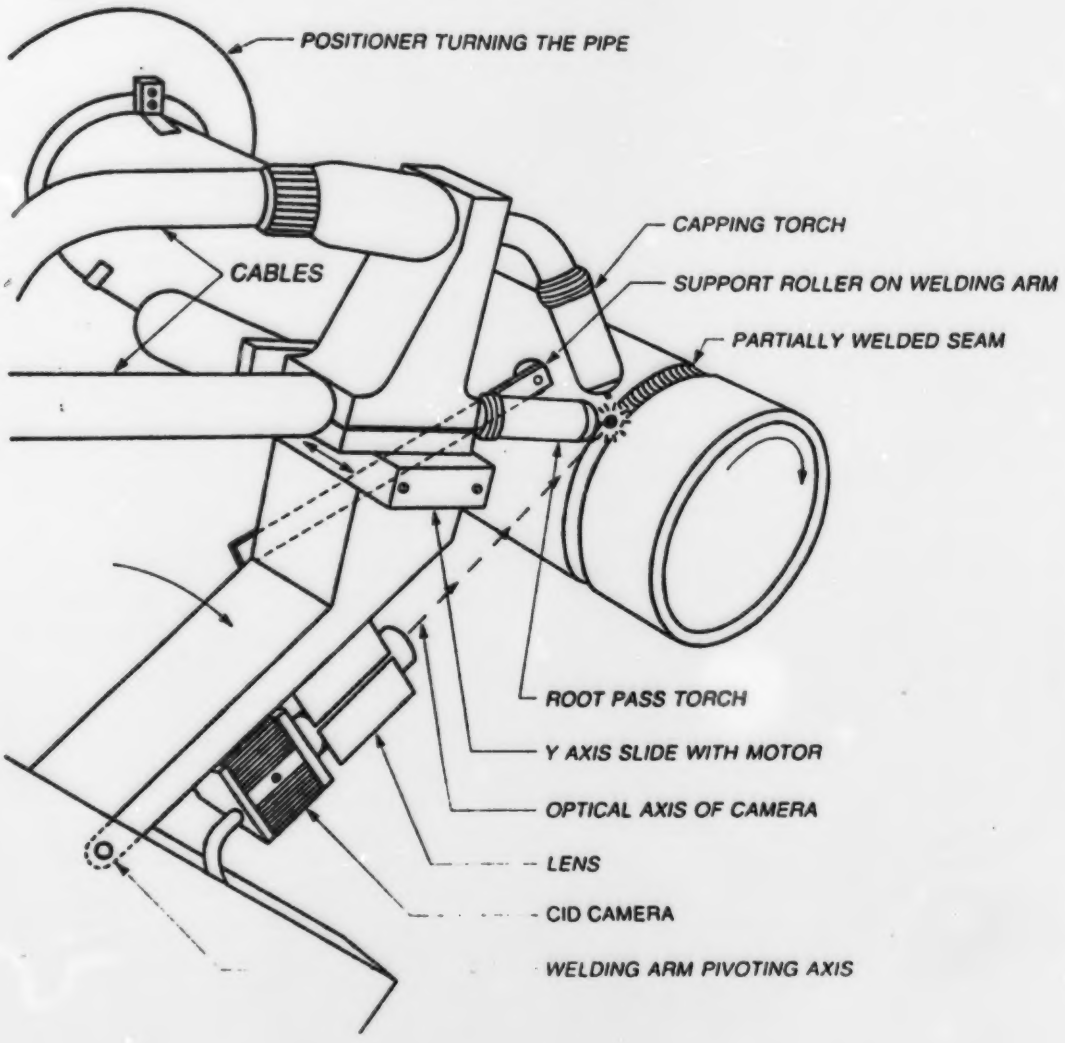
Figure 5: Pipe welding prototype.

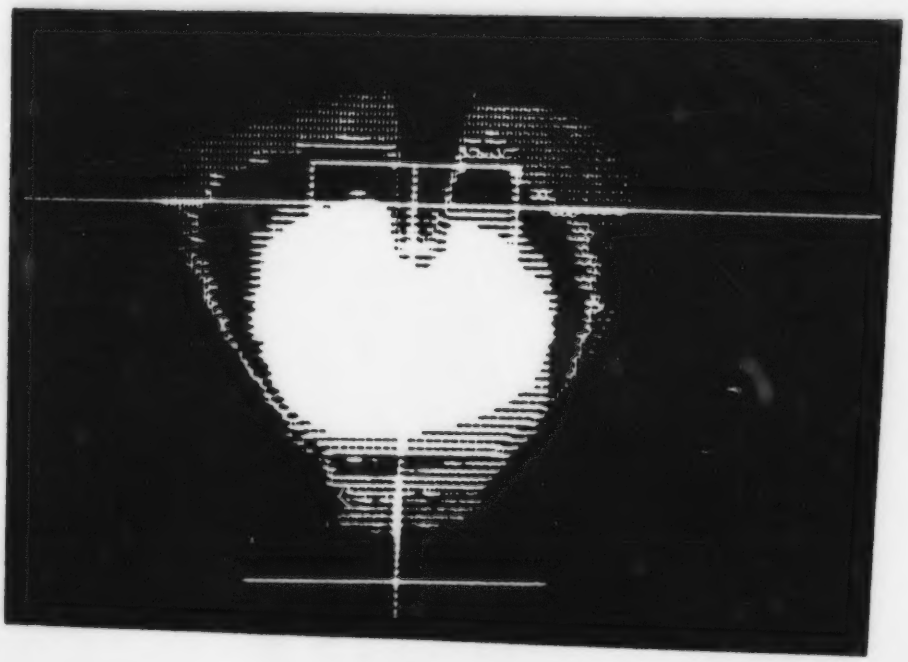
Figure 6: Safe operating range of the process in terms of tolerances on the preparation.

Figure 7: Travel speed (in inches per minute) as a function of time for a root pass on a 6" pipe.

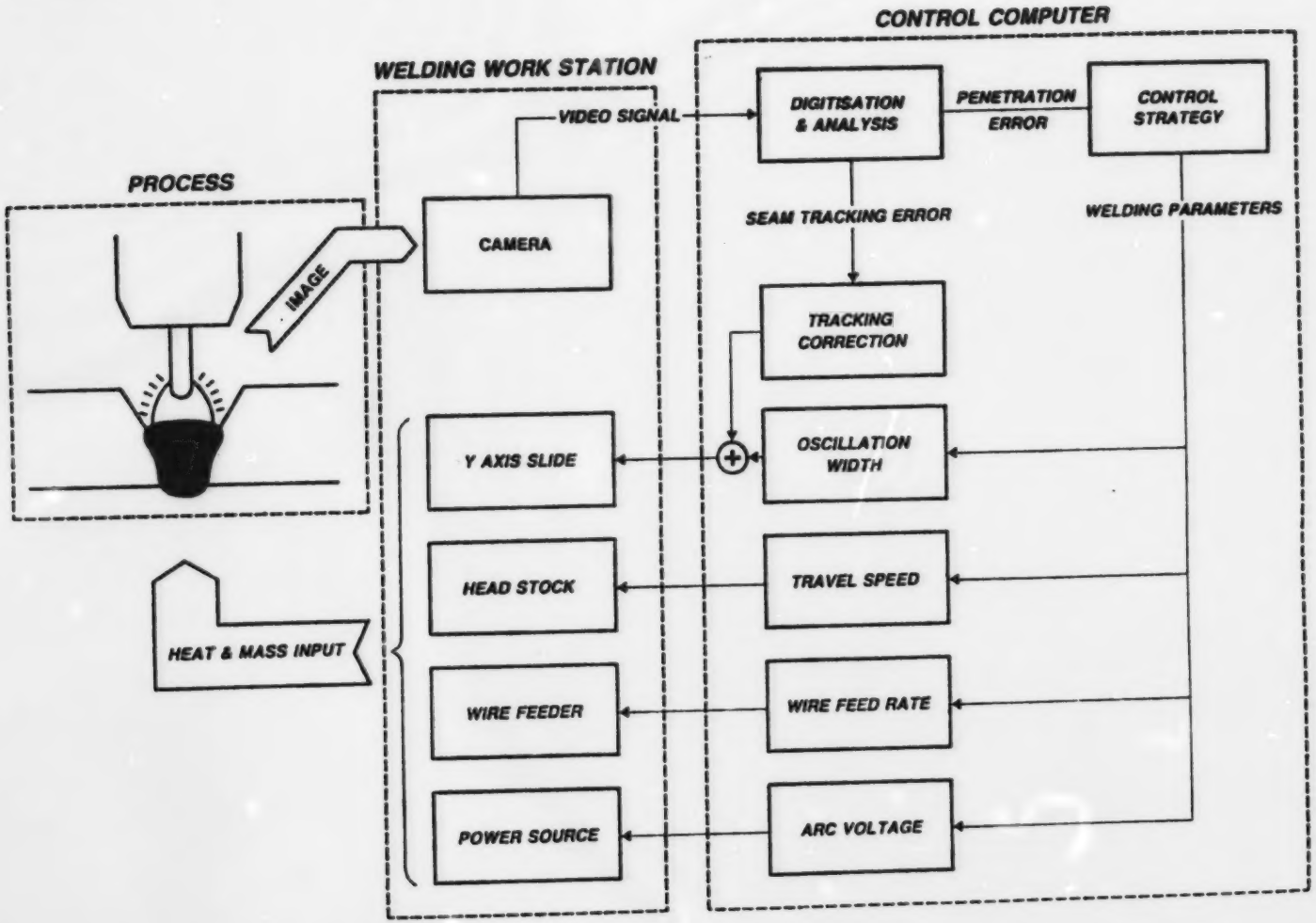

Gap
Misalignment
Land
Cap
Root Pass

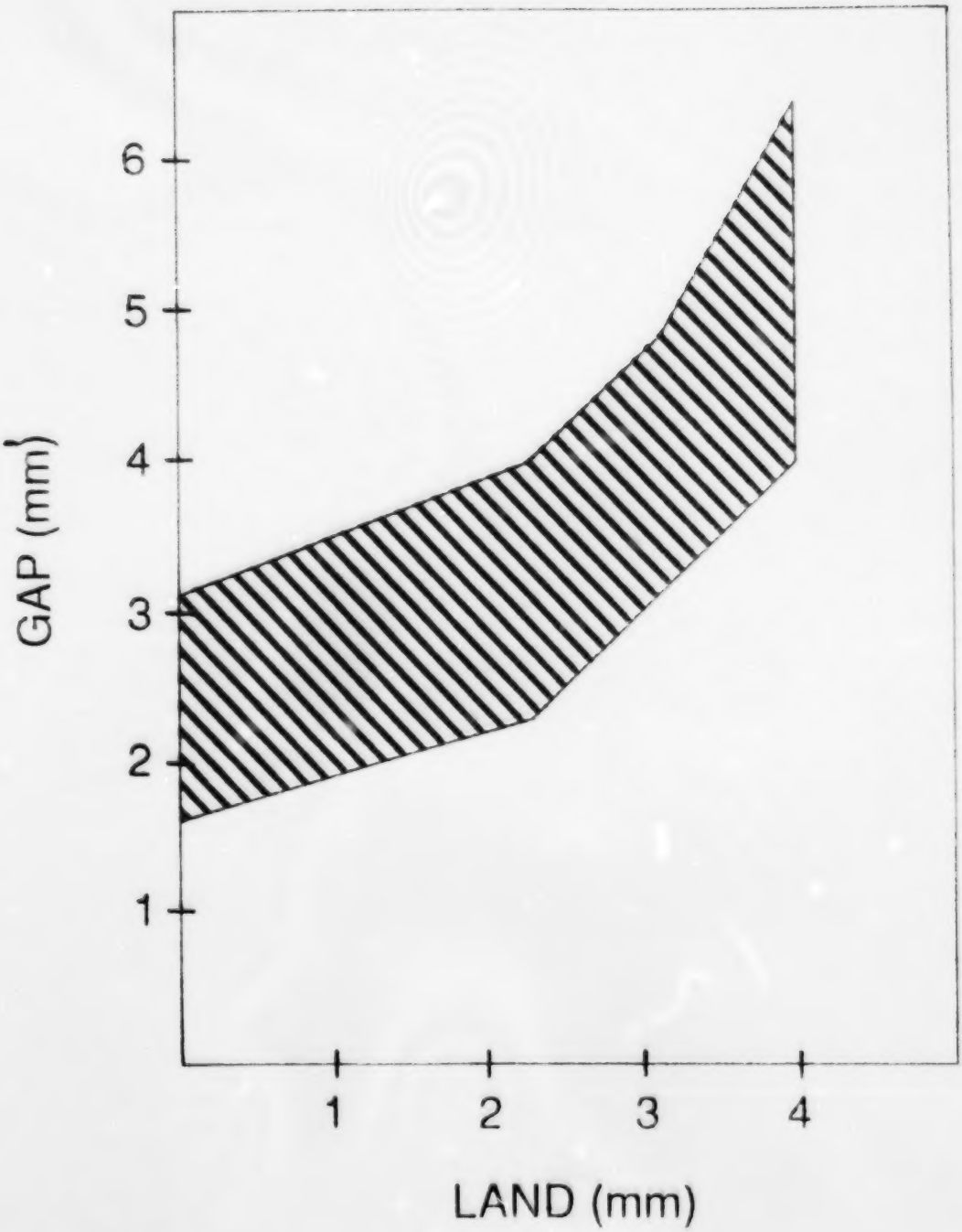
WELDING ARM

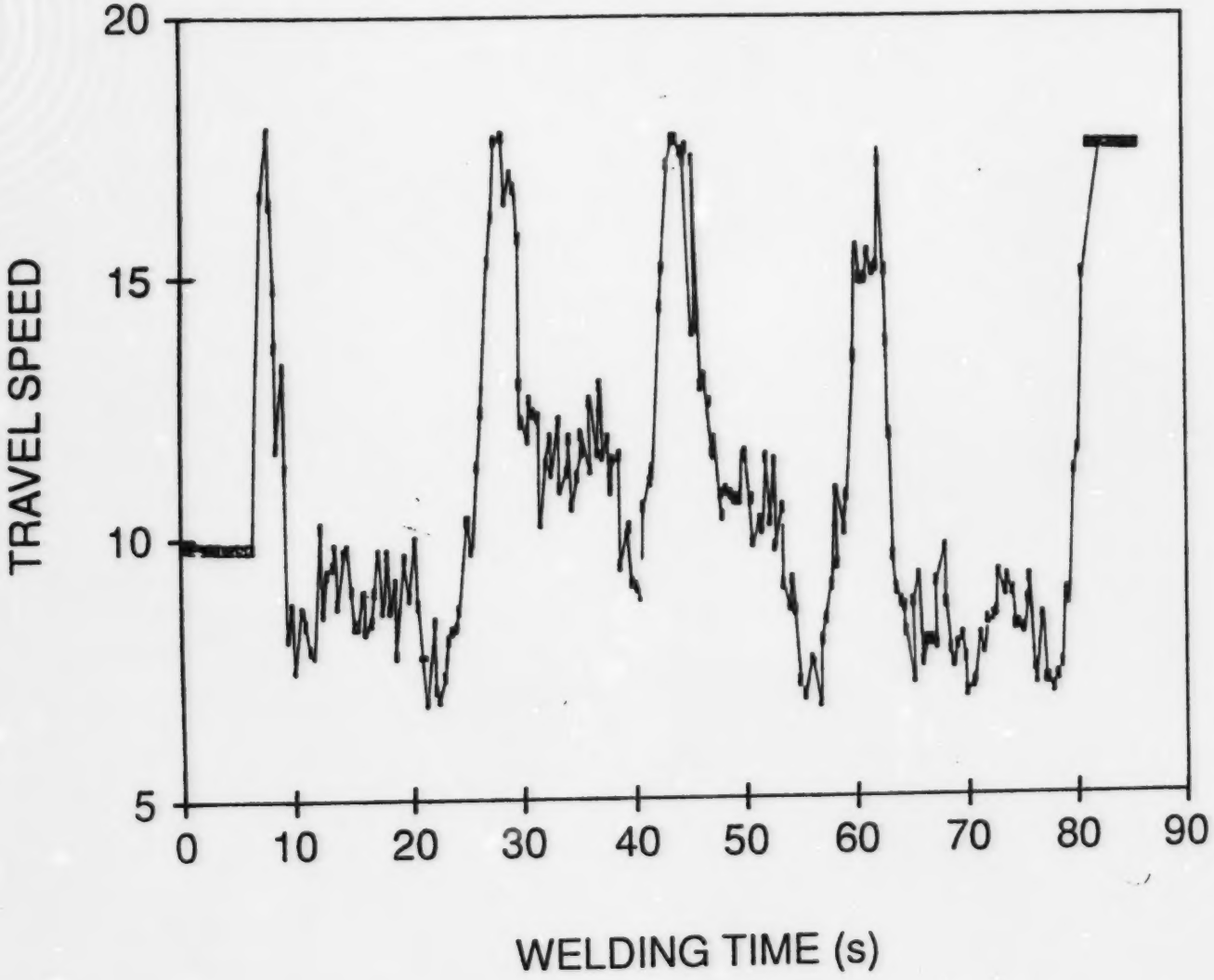

POSITIONER TURNING THE PIPE
CABLES
CAPPING TORCH
SUPPORT ROLLER ON WELDING ARM
PARTIALLY WELDED SEAM
ROOT PASS TORCH
Y AXIS SLIDE WITH MOTOR
OPTICAL AXIS OF CAMERA
LENS
CID CAMERA
WELDING ARM PIVOTING AXIS



SCHEMATIC DIAGRAM OF THE ADAPTIVE PIPE WELDER




GAP (mm)
6
5
4
3
2
1
1
2
3
4
LAND (mm)


20
15
10
5
TRAVEL SPEED
0
10
20
30
40
50
60
70
80
90
WELDING TIME (s)